ECE 371
Materials and Devices

10/29/19 - Lecture 18

Einstein Relation, PN Junctions, Built-In Potential, Built-In Electric Field

General Information

- Homework 6 assigned and due 11/07
- Homework 5 solutions posted
- Midterm #2 on 10/31, covers Ch. 3, 4, 5. Closed book, one 8.5” x 11” sheet (front and back) allowed.
- Example problems from previous midterm posted
- Video of midterm 2 review session posted
- Reading for next time: 7.2 and 7.3

The Einstein Relation

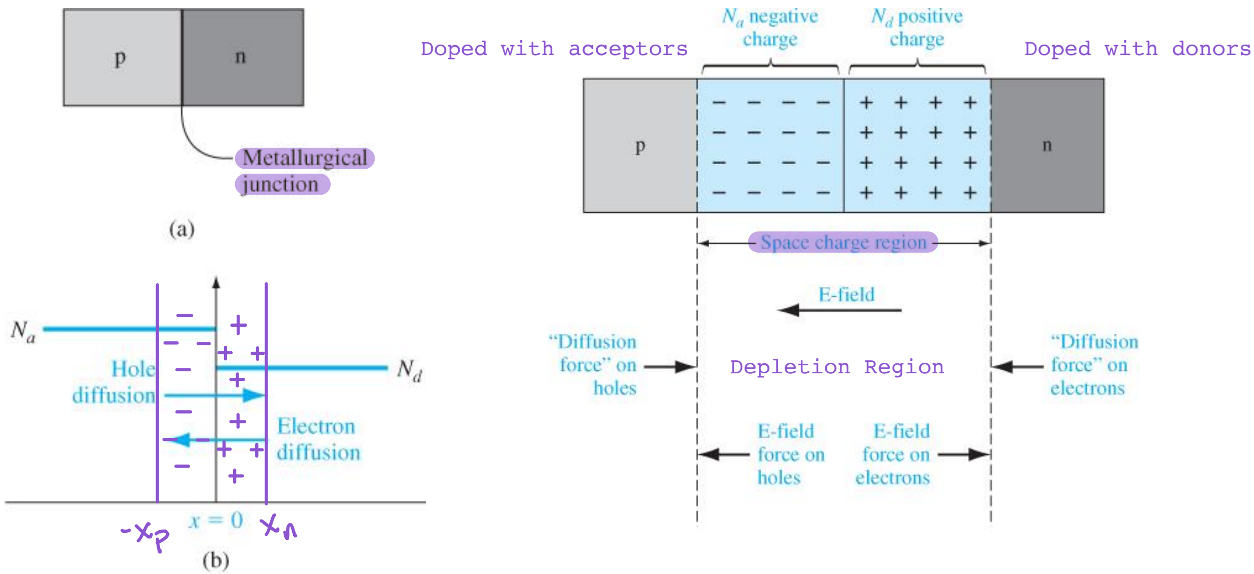
$$\boxed{\frac{D_n}{\mu_n} = \frac{D_p}{\mu_p} = \frac{kT}{e}}$$

- Einstein relations relate the diffusion constants to the mobilities
- Temperature dependence of the diffusion constants is the result of the temperature dependence of the mobilities (e.g., lattice and ionized impurity scattering)
- The diffusion constants are ~40X smaller than the mobilities at room temperature

Table 5.2 | Typical mobility and diffusion coefficient values at $T = 300$ K ($\mu = \mathrm{cm^2/V\text{-}s}$ and $D = \mathrm{cm^2/s}$)

	μ_n	D_n	μ_p	D_p
Silicon	1350	35	480	12.4
Gallium arsenide	8500	220	400	10.4
Germanium	3900	101	1900	49.2

pn Junction - Basics



- Majority carriers diffuse to the opposite side and become minority carriers where they recombine
- Diffusion current is balanced by drift current Can't have net current, no external forces
- Depletion approximation is assumed (step-like junction)
- Doping on the n and p sides is assumed to be uniform
- In the space charge (depletion) region electrons and holes are swept out by the electric field

pn Junction – Built in Potential

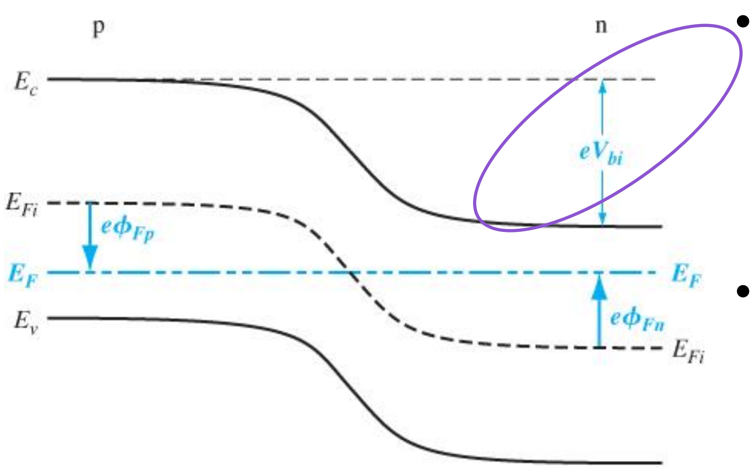


Figure 7.3 | Energy-band diagram of a pn junction in thermal equilibrium.

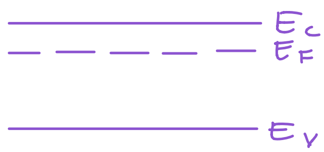
$$\boxed{V_{bi} = \overset{0.0259}{\frac{kT}{e}} \, ln\left(\frac{N_d N_a}{n_i^2}\right)}$$

Doping dependence so ex GaAs -> higher Vbi

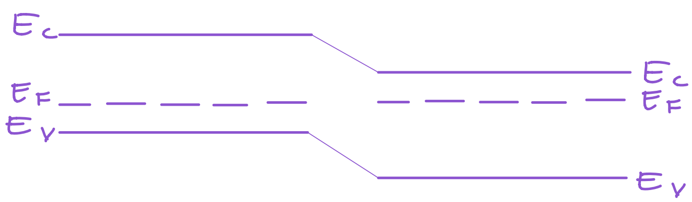
- A potential barrier forms across the junction for holes moving left to right and electrons moving right to left
- N_a and N_d now refer to the total net impurity concentration on either side of the junction
- The built-in potential varies with the doping concentrations, but only slightly
- V_{bi} for silicon is ~ 0.7 V
- For very high doping, V_{bi} is approximately E_g/e

Align the p and n-type

P-type



N-type



Example 7.1

Objective: Calculate the built-in potential barrier in a pn junction. **EXAMPLE 7.1**

Consider a silicon pn junction at $T = 300$ K with doping concentrations of $N_a = 2 \times 10^{17}$ cm^{-3} and $N_d = 10^{15}$ cm^{-3}.

■ Solution

The built-in potential barrier is determined from Equation (7.10) as

$$V_{bi} = V_t \ln\left(\frac{N_a N_d}{n_i^2}\right) = (0.0259) \ln\left[\frac{(2 \times 10^{17})(10^{15})}{(1.5 \times 10^{10})^2}\right] = 0.713 \text{ V}$$

If we change the doping concentration in the p region of the pn junction such that the doping concentrations become $N_a = 10^{16}$ cm^{-3} and $N_d = 10^{15}$ cm^{-3}, then the built-in potential barrier becomes $V_{bi} = 0.635$ V.

■ Comment

The built-in potential barrier changes only slightly as the doping concentrations change by orders of magnitude because of the logarithmic dependence.

Built-In Electric Field

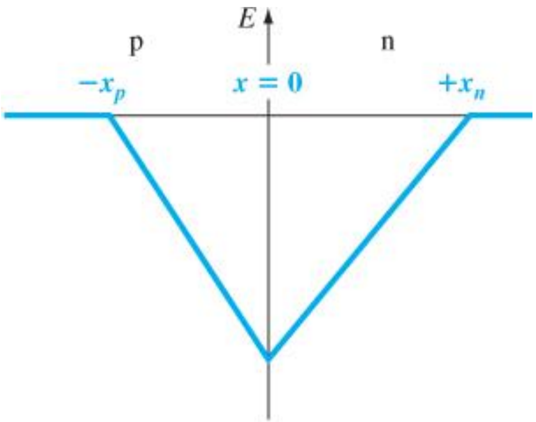


Figure 7.5 | Electric field in the space charge region of a uniformly doped pn junction.

- Built-in electric field is present even without an applied bias
- E-field is negative since it points in the –x direction
- Maximum magnitude of E-field occurs at the junction

Higher doped side has larger depletion region

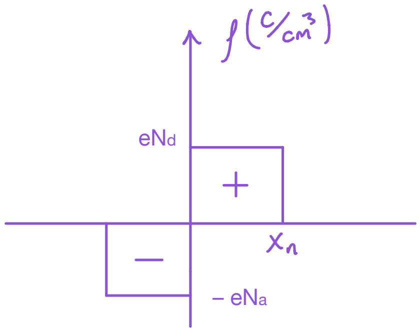
$$\boxed{E(x) = \frac{-eN_a}{\varepsilon_s}(x + x_p) \text{ for } -x_p \le x \le 0}$$

$$\boxed{E(x) = \frac{-eN_d}{\varepsilon_s}(x_n - x) \text{ for } 0 \le x \le x_n}$$

$$\boxed{N_a x_p = N_d x_n}$$

# of charges per area on the n and p sides are equal

Electric Field



$\rho_p = -eN_a$

$\rho_n = eN_d$

ρ is volume charge density

ε_s is permittivity of semiconductor

Built-In Potential

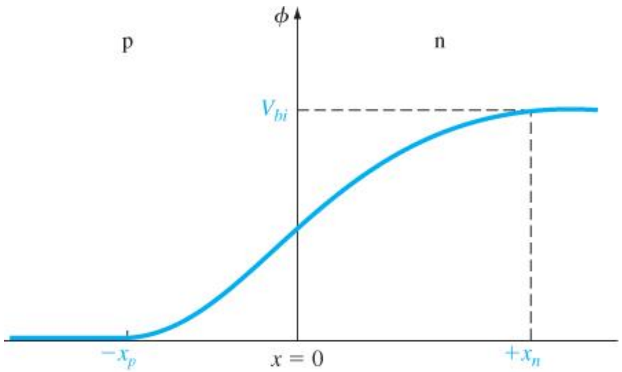
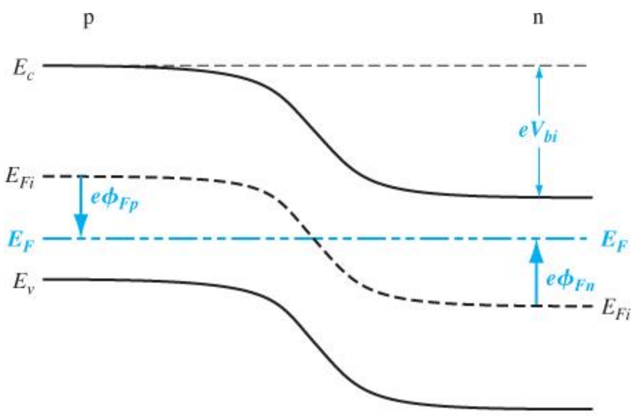


Figure 7.6 | Electric potential through the space charge region of a uniformly doped pn junction.



- Quadratic dependence of potential on distance
- Plot applicable to electrons and holes
- Holes:
  - Lower potential on the p-side
  - Lower potential energy on the p-side
- Electrons:
  - Lower potential on the p-side
  - Lower potential energy on the n-side
- Built-in potential causes "diode" behavior – blocks current at zero bias

$$\boxed{V_{bi} = \frac{e}{2\varepsilon_s}\left(N_d x_n^2 + N_a x_p^2\right)}$$